nuSTORM PION BEAMLINE DESIGN UPDATE*

A. Liu†, A. Bross, D. Neuffer, Fermilab, Batavia, IL, 60510, USA
S.Y. Lee, Department of Physics, Indiana University, Bloomington, IN, 47405, USA

Abstract

A facility producing neutrinos from muons that decay in a racetrack ring can provide extremely well understood neutrino beams for oscillation physics and the search for sterile neutrinos. The "neutrinos from STORed Muons"(nuSTORM) facility based on this idea has been introduced by Bross, Neuffer et al. The design of the nuSTORM facility and the particle tracking have been presented in the paper of Liu, et al. This paper demonstrates the recent optimization results of the pion beamline, with G4beamline simulations. The optimum choice of pion beam center momentum, a new algorithm on fitting bivariate Gaussian distribution to the pion phase space data at the downstream side of the horn, and the comparison of the beamline performance with the optics designed based on Graphite and Inconel targets are also described.

INTRODUCTION

The overview of the nuSTORM project can be found in the nuSTORM Fermilab proposal [1]. A possible nuSTORM facility design was described in the paper of Liu, et al. [2]. An overview of the facility is displayed in Figure 1. In order to obtain as many useful muons from pion decay as possible, the pion beamline is designed to capture and transport pions within a $P_0 \pm 10\%$ GeV/c momentum range, where P_0 is the design momentum of the pion beamline [3]. P_0 is chosen to maximize the muon flux within a $3.8 \pm 10\%$ GeV/c range. This paper finds P_0=5 GeV/c, as determined by G4Beamline[4] simulations. We also inspect the possibility of using an Inconel target where the pion productivity is checked and compared with the graphite target scenario we proposed in our previous papers.

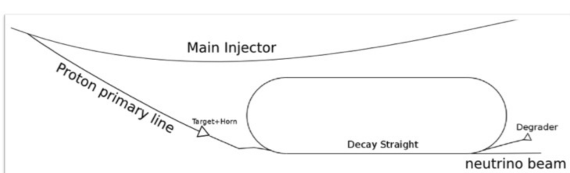

Figure 1: Overview of the nuSTORM facility. The Fermilab Main Injector places proton beam on a target, producing a large spectrum of secondary pions that are transported and injected into the decay ring. The pions then decay within the decay straight to muons , which are captured by the ring. Muons decay and produce neutrino beams with known flux and flavor in the decay straight.

Pions are produced by protons hitting the target, collected by a magnetic horn, transported and injected into the ring by a Beam Combination Section (BCS) and transmitted to the end of the decay straight until extracted. The beamline from the downstream end of the horn to the end of the racetrack ring decay straight is called the pion beamline of nuSTORM. A schematic drawing of the pion beamline in G4Beamline is shown in Figure 2.

PION PRODUCTION AND COLLECTION

nuSTORM is designed to use a 100 kW target station. A proton pulse with approximately 10^{13} protons at 120 GeV and pulse length of 1.6 μs will be extracted from the Fermilab Main Injector and bombarded onto a solid target. The target is partially inserted into a NuMI-like, 300 cm long magnetic horn to collect the pions produced from the target. The horn shape and length are designed to optimize the acceptance of pions within a momentum range of $P_0 \pm 10\%$. A schematic drawing of the horn with the target is shown in Figure 3

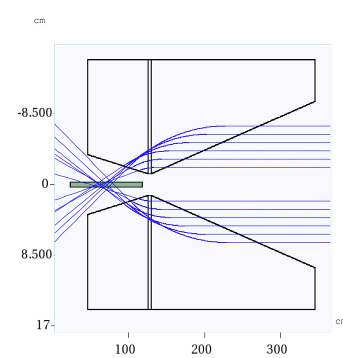

Figure 3: Schematic drawing of the nuSTORM horn and target (middle rod). Protons hit the target from the left.

Selecting The P_0 of The Pion Beam

The probability density of having a muon with momentum p_μ from the decay of a highly relativistic pion is $1/(2\gamma p'_\mu)$ for $0.573P_0 \le p_\mu \le P_0$, where γ is the relativistic gamma of the pion, and $p'_\mu = 29.8$ MeV/c is the muon momentum in the rest frame of the pion. Assuming the pion beam has a uniform momentum distribution over the range [$0.9P_0$, $1.1P_0$], the probability of having a muon with momentum p_μ from this pion beam has a maximum constant value

$$f(p_\mu) = \int_{0.9P_0}^{1.1P_0} \frac{1}{0.2P_0} \frac{m'_\pi c}{2p_\pi p'_\mu}\, dp_\pi = \frac{2.35}{P_0} \left(\frac{\text{muons}}{\text{MeV/c}}\right)$$

* Work supported by DOE under contract DE-AC02-07CH11359
† aoliu@fnal.gov, also affiliated to Indiana University, supported in part by DE-FG02-12ER41800 and NSF Phys 1205431

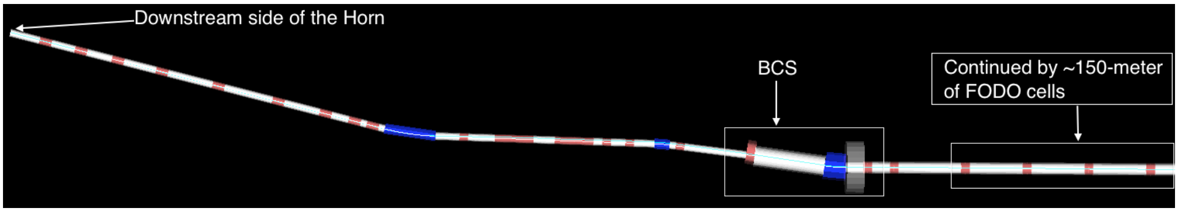

Figure 2: A schematic drawing of the pion beamline. The pions move from the downstream side of the horn (left) to the end of the decay ring straight section (right, not shown all).

for $0.63P_0 \leq p_\mu \leq 0.90P_0$. m'_π=139.6 MeV/c is the pion mass in the rest frame of the pion. This implies that the momentum distribution of the muons within the 3.8±10% GeV/c momentum acceptance of the ring is uniform as long as P_0 ∈[4.644, 5.426] GeV/c. In addition, the value $2.35/P_0$ of the flat top of $f(p_\mu)$ is smaller when P_0 is larger. Having a lower P_0 will result in more muons within $3.8 \pm 10\%$ GeV/c, whereas having a higher P_0 will reduce the requirement on dispersion, D_x, created by the BCS and will reduce the emittance growth from pion decay. Figure 4 shows the trade-off by plotting the number of muons in the momentum acceptance with $\sigma_{x'}$ and $\sigma_{y'}$, which are the rms angle width of the muons. The smaller $\sigma_{x'}$ and $\sigma_{y'}$ are, the easier the muon beam can be captured. The criteria are well-balanced when P_0 is 5 GeV/c.

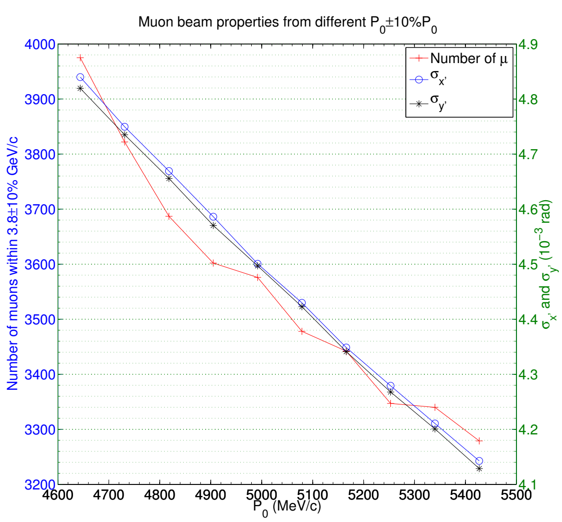

Figure 4: Number of muons within $3.8 \pm 10\%$ GeV/c from the decay of pion beams with different $P_0 \pm 10\% P_0$ (In red crosses, left vertical axis), $\sigma_{x'}$ and $\sigma_{y'}$ (In blue circles and black stars, right vertical axis) v.s P_0. The number of pions in each simulation bin is 10^4.

Target and Horn

We use a 95 cm graphite target (about two interaction lengths), with a radius of 3 mm as a baseline in our design. A 39 cm Inconel target (also two interaction lengths), with the same radius has also been considered and with it we obtain more pions within the above momentum range. The engineering prospects of the Inconel target are under study. The number of pions within 5±10% GeV/c we collect after the horn is 0.139 and 0.157 pions per POT for the graphite and Inconel targets, respectively.

Algorithm for Fitting a Gaussian Function to the Pion Distribution

In order to design the pion beamline optics, the TWISS parameters need to be matched at the downstream side of the horn. Because the pion distribution in the transverse phase space is dramatically distorted from an ideal Gaussian beam, we need to find an algorithm to fit a bivariate Gaussian distribution to the phase space data. One way to do so is by using a thorough scan on the TWISS parameters and including the maximum number of pions with the acceptance ellipse. However, this scan efficiency is greatly limited by its step size and the initial starting point of the parameters. We implemented the Gauss-Newton method of minimizing the sum of squared function $Q(\vec{\alpha}) = \sum_{i=1}^{n} r_i^2(\vec{\alpha})$ where $\vec{\alpha} = (\mu_t, \mu_{t'}, \sigma_t, \sigma_{t'}, \rho_{t,t'})$ represents a list of variables in the function r_i, which in our fitting purpose represents the residuals of $r_i(\vec{\alpha}) = \ln z(t,t')_i - \ln f((t,t')_i, \vec{\alpha})$. t and t' represent the transverse phase space coordinates in either x or y direction, $z(t,t')_i$ is the real bivariate probability density value at $(t,t')_i$ and $f((t,t')_i$ is the Gaussian function value at that point. The vector $\vec{\alpha}$ is optimized by iterating on m in the expression $\vec{\alpha}^{(m+1)} = \vec{\alpha}^{(m)} - (\vec{J}^\top \vec{J})^{-1} \vec{J}^\top \vec{r}(\vec{\alpha})$ until the difference of $\vec{\alpha}^{(m+1)}$ and $\vec{\alpha}^{(m)}$ has decreased to a critical value. Once the $\vec{\alpha}$ is found, we can use the covariance matrix to get the TWISS parameter values.

The direct Gauss-Newton method still has large inaccuracy because we include all the pions in the phase space in the fitting. However, some of those particles are far outside the 2×10^{-3}m·rad acceptance ellipse of the pion beamline. Thus we did another iteration on the Gauss-Newton method, where each time we discard a number of pions having the largest phase space emittance. The iteration is repeated until the rms phase space emittance of the beam has shrunk to 2×10^{-3}/6 m·rad, which is the conventional way of defining the relation between rms emittance and acceptance.

The comparison of the fitting results from the parameter scan method and the iterative Gauss-Newton method are shown in Figure 5, taking the pions produced by the

ISBN 978-3-95450-138-0

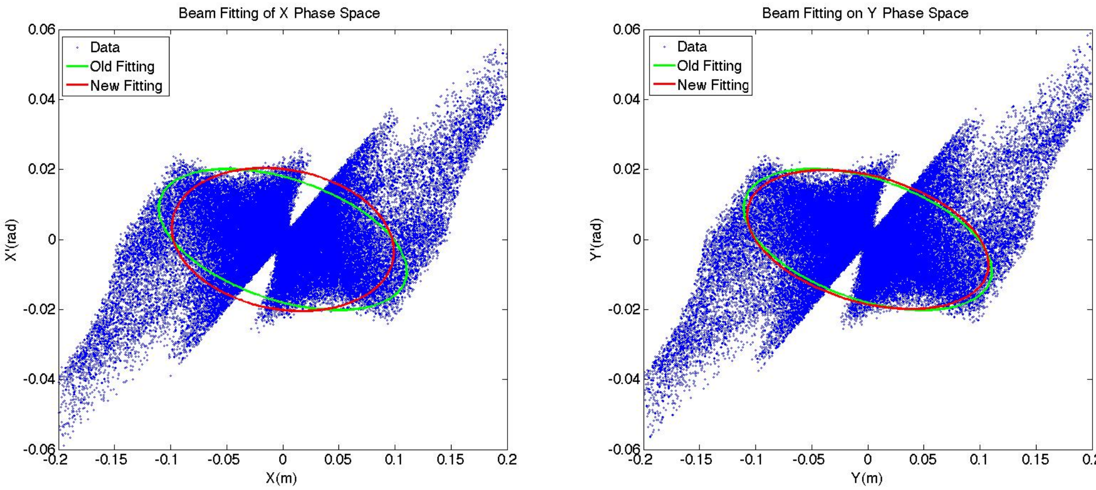

Figure 5: Comparison of acceptance ellipses in the horizontal phase space (left) and vertical phase space (right) using different fitting methods. The old scanning method and the new Gauss-Newton method are plotted in green and red, respectively.

graphite target as an example. The new acceptance ellipse contains approximately 1% more pions than the previous one does. The TWISS parameters from the direct Gauss-Newton method, parameter scan method, and the iterative Gauss-Newton method are shown in Table 1.

Table 1: TWISS Parameters from Different Fitting Methods

method	α_x(1)	β_x (m)	α_y (1)	β_y (m)
Direct Gauss-Newton	-0.21	5.28	-0.58	6.32
Parameter Scan	0.5	6.13	0.5	6.13
Iterative Gauss-Newton	0.17	4.91	0.38	5.8

Pion Beamline Performance

After the TWISS parameters are found at the downstream side of the horn, the optics of the pion beamline can then be matched to the racetrack ring decay straight, where the periodic TWISS parameters were set by optimizing a series of design criteria [5]. The performance comparison of pion beamlines designed based on the optics of pions from graphite and Inconel targets is shown in Table 2.

SUMMARY

The nuSTORM pion beamline design has been updated. The optimization of the beamline confirms an optimum center momentum of the pion beam at 5 GeV/c, and a new algorithm of particle distribution fitting has been tested. The yield of muons within 3.8±10% GeV/c within the first pass of the decay straight is about 0.008 for graphite target and 0.013 for Inconel target, per 120 GeV POT.

Table 2: Pion Beamline Performance Comparison

Target	π^+ at the downstream side of the horn (per POT)	π^+ at the end of the decay straight (per POT) (without decay)
Graphite	0.140	0.081
Inconel	0.157	0.114

Target	$\mu+$ in 3.8±10% GeV/c at the end of the decay straight (per POT) (with decay)
Graphite	0.008
Inconel	0.013

ACKNOWLEDGMENT

We thank the APC colleagues who provided comments and suggestions on the design of the nuSTORM facility.

REFERENCES

[1] P. Kyberd et al. “Neutrinos from STORed Muons: Proposal to the Fermilab Physics Advisory Committee” arXiv:1308.6288.

[2] A. Liu et al., “nuSTORM Facility Design And Simulation”, proceedings of iPAC2013, p55 (2013).

[3] A. Liu et al., “Determining the pion reference momentum for nuSTORM injection design”, Fermilab TechNote, Fermilab-TM-2563-APC (2013).

[4] G4beamline, T. Roberts, Muons, Inc.

[5] A. Liu et al., “Design and simulation of the nuSTORM pion beamline”, submitted to PRST-AB (2013).